Energy Optimization for Bidirectional Multimedia Communication in Unsynchronized TDD Systems

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***Abstract*—Energy efficiency is one of the main system resources that has to be optimally allocated, due to its impact on the amount of generated interference and the battery life for multimedia communication. In this paper we concentrate on the Time Division Duplexing (TDD) option, and how to efficiently allocate energy on both Uplink (UL) and Downlink (DL) channels that share the same bandwidth but over different time intervals. One of the main advantages of TDD is the possibility for load compensation between UL and DL, by allocating a larger percentage of time for the operation in DL if the system is congested in DL, and viceversa. While this allocation can be done on each cell independently, the result is that adjacent cells would have a different compensation value, thus generating cross interference that decreases the system performance, mainly on the cell-edge users. This paper presents an energy allocation in order to compensate the unsynchronization in the percentage allocation, where the objective is to guarantee minimum Quality of Service (QoS) satisfaction at all receivers, while the least amount of energy is consumed.**

***Index Terms*—Multimedia communication, energy efficiency, bidirectional applications, unsynchronized TDD, LTE-A, interference.**

I. Introduction

One of the most interesting technologies that has been recently standardized is the Long Term Evolution - Advanced (LTE-A) [1]. It is designed to meet the growing performance requirements of mobile broadband in general and multimedia communication in particular; where several countries had implemented LTE-A with extraordinary results. LTE-A is mainly operated with its Frequency Division Duplexing (FDD) feature in many countries, but the standard also enables the Time Division Duplexing (TDD) version [1], that got the attention of China, India and many Middle East countries, that prefer the TDD bandwidth management over the FDD benefits. Field implementations show the easier implementation of TDD systems in comparison to FDD [2], and with higher performance indicators, which attracted more attention to TDD. Recent studies proposed TDD as the only duplexing strategy for 5G systems [3].

Enhancing the throughput and the Quality of Service (QoS) are the main objectives of LTE-A, while reducing the energy consumption. Therefore, less interference, higher battery life at the user equipment (UE) and less cost for the operators are obtained. Green low-energy communication is a hot topic that attracted a high number of researchers; and it found its way into realistic implementation in several standards [4].

TDD main advantage is that the same bandwidth is used for Uplink (UL) and Downlink (DL), so higher efficiency is obtained to enable better multimedia communication. Moreover, as UL and DL use the same frequency, then the system does not need a duplexer, that is known to be a high energy consuming unit in transceivers [2]. Former wireless systems are more focused on the DL performance as users wanted to download multimedia content from servers, but the current trend with more impact and emphasis of the bi-directional applications like video-calls, online games and social networking changes the way how the UL is considered and optimized. Multimedia applications with its bi-directional requirements are a major challenge for wireless systems as they need a special resource allocation strategy, and TDD seems a strong candidate to efficiently tackle this challenge. The TDD scheme is more dynamic and allows a continuous change in the allocations for UL and DL to match with any user/operator requirements. Thus, it is suitable in heterogeneous multimedia scenarios with a a large number of applications, where each one of them asks for different requirements; which is the expected situation for 5G networks [5].

TDD systems have received large attention recently, where [6] studied the interference between TDD and FDD systems and how the two systems can coexist, while [7] proposed interference coordination in a relaying transmission over TDD. Upgraded features are also considered in TDD as the impact of channel errors in the beamforming [8] for multiple antenna systems. The UL-DL joint consideration is tackled in TDD with a cell selection mechanism in [9] and the pilot signal energy efficiency for the multiuser multiple antenna environment is optimized in [10] [11], all of them showing the benefits behind the consideration of TDD systems.

TDD systems are also proposed with all novel technologies, as its impact is analyzed through the application of small cells in [12] and how to efficiently allocate the resources to decrease the interference, whereas the carrier aggregation technique is studied in [13] when applied to TDD systems. An interesting work that tackles the impact of traffic patterns on the dynamic ratio selection is presented in [14], where power control mechanisms are also introduced.

In TDD systems and as its name indicates, the separation between DL and UL is carried out in the time domain, so the decision on the UL/DL ratio is very important to denote the percentage of time allocated to each link [5], which adapts to the scenario and applications requirements. This decision is very important as it extracts the TDD benefits to enhance its performance [5]. Previous TDD systems (e.g. WiMAX) use a constant UL/DL ratio in all the system cells; but to grasp all

TDD advantages, a dynamic ratio over the time and the cells is required, which translates into high interference among adjacent TDD cells as some cells can be in DL while other in UL, and an interference uncontrolled scenario is obtained. This unsynchronization is harmful to the system performance and novel mechanisms to control it are required. To sum-up, to increase TDD performance the UL/DL ratio must be variable but this ”variability” induces interference, and this paper will propose a mechanism to mitigate this interference between the users (UEs) and base stations (eNBs), to enable smooth multimedia communication among them.

This problem is not new as it has been already detected in commercial systems and in field tests [2], and the standard tackled this issue and it proposed interference cancellation mechanisms at the receiver sides [6]. Its drawback is the UE higher cost and increased energy consumption, so that some rollouts avoided these mechanisms by avoiding overlap among the TDD cells and having them as hot spots. This temporary solution is valid as long as LTE-A is not the main access technology and only considered as a hot-spot setup for some specific locations (e.g., airports, train stations, coffee shops). However, the number of LTE-A cells is currently increasing and the interference problem will soon become a serious issue that has to be solved in order to obtain all LTE-TDD advantages.

This paper is focused on this problem through a new mechanism to mitigate the interference to cell-edge UEs. It offers a novel energy allocation technique for TDD unsynchronized systems, as it formulates the exact energy allocated to each entity in the scenario (UEs and eNBs) to satisfy the QoS demands for the system, while the least amount of generated interference and consumed energy are obtained. The problem is denoted through a mathematical linear optimization problem [5] and the optimum allocated energy is shown in a closed form equation with all the involved system parameters.

Several techniques are proposed in literature for energy allocation, [15] presents the energy allocation over cognitive bands, while [16] tackles the energy efficiency when traffic kinds are taken into consideration. An alternative strategy to enhance the system performance and optimize its resources is through prediction, as shown in [17] and [18]. None of previous proposals applies to TDD unsynchronization, thus the current paper achievements are not comparable.

As a summary, the contributions of this paper are in the field of energy efficiency over TDD unsynchronization in UL/DL multimedia applications as follows

- TDD system unsynchronization is highlighted for adjacent cells when UL/DL ratios are variable.
- An energy allocation scheme is proposed to mitigate the impact of unsynchronization in the network.
- QoS requirements are considered for the energy allocation scheme to match the design to multimedia commercial systems.
- Closed form mathematical formulations are obtained with all the involved system parameters to identify their impact. They show a perfect match when compared to computer simulations.

The remainder of this paper is organized as follows: section II introduces the system model and the considered scheduler for UL/DL communication, followed by III with the different operation cases for TDD systems. Section IV will tackle the proposed energy allocation technique while section V is devoted to the computer simulations. The paper finally draws the conclusions in section VI.

II. System Model

The dense LTE-A setup is tackled to show the impact when TDD cells overlap, where we assume that overlap happens among the eNBs, with a total of M available eNB in the considered area, where each one transmits/receives multimedia traffic to/from one user terminal out of S available single-antenna users. A quasi static block fading channel $h(t)$ is assumed between the eNB and each one of the users. The channel is characterized by independent and identically distributed (i.i.d.) complex Gaussian entries $\sim \mathcal{CN}(0,1)$. To improve the system metrics performance, each eNB performs a scheduling over the UEs to select the one with best channel characteristics at each scheduling time, as will be shown in next section through a novel joint UL/DL Opportunistic Scheduling technique. The scenario is running the TDD technique, so that $h_{s,m}(t)$ denotes the channel both in UL and DL with for the s^{th} selected user by the m^{th} eNB. Because of the bandwidth scarcity, full frequency reuse over the M TDD cells is assumed so that interference is generated among the eNBs and their selected users. For ease of notation, time index is dropped whenever possible. All used mathematical symbols along the paper are listed in Table I.

Symbol	Notation
M	Number of eNBs
S	Number of users
h	Wireless channel
UL	Uplink
DL	Downlink
ξ_d	SNIR downlink threshold
ξ_u	SNIR uplink threshold
α	Ratio UL-DL
y	Received signal
x	Transmitted signal
z	AWG Noise
P	Power
σ^2	Noise variance
E_t	Total consumed energy
T_s	Slot time
$\mathbf{e}$	Energy allocation vector
$\mathbf{e}^*$	Optimal energy allocation vector

Table I: Mathematical Symbols

In order to guarantee QoS minimum demands, we fix a predefined threshold ξ_d on the DL Signal to Noise and Interference Ratio (SNIR) value, while the eNB will also apply a threshold to the SNIR values in the UL (ξ_u) in order to ensure the correct reception of multimedia packets. This will guarantee that any selected user satisfies the minimum threshold in both UL and DL.

UL and DL have the same channel and bandwidth, as as previously said, they are only distinguished by the time allocated to each link, therefore, a crucial task in TDD is to decide on the best ratio UL-DL (α) that defines the percentage from the slot time T_s that each link is operated, which is predefined in the LTE-A specs [19] as Transmission Time Interval (TTI) $= 1ms$. For example, for bidirectional systems the value of $\alpha = 50\%$ is considered. Former TDD systems (like IEEE 802.16e) define the α value based on the average load in UL and DL, and the same α is applied over the whole network; thus avoiding the problem of interference. But the heterogeneity of multimedia applications, that change instantaneously and in a different way over adjacent cells, motivates a dynamic α that adapts to the application requirements in order to enhance the system performance and capabilities [20].

The drawback of adaptive α values is the cross-interference that it creates among adjacent eNBs and selected users due to the unsynchronization of the UL-DL ratio. Before tackling the different regions characterization and the proposed energy allocation, we now describe the UL-DL opportunistic scheduling among the users in each cell.

A. UL-DL Opportunistic Scheduling (OS)

The Opportunistic Scheduling (OS) [21] [22] is one of the essential users' selection techniques in multiuser scenarios. Through the acquisition stage a predefined training sequence is dispatched to all the users in the system to enable each one to measure its received signal quality then return it back to the eNB [8]. The user with the best received quality will be selected by the scheduler to take advantage of its current channel situation. As a result, it will enhance the whole system behaviour. This technique delivers a high level of data rate performance, and it is widely used in commercial systems as HSDPA and LTE-A cellular standards [1].

Another TDD advantage is the no demand for feedback about the channel instantaneous behavior, as the same channel is used for UL and DL (i.e., reciprocal channel). This means that TDD systems are more efficient in the use of network overhead, which motivates its use by operators [23]. However, in actual implementation the UEs receive a huge interference from adjacent eNB. And as a consequence, channel reciprocity does not hold making the transmitter to be blind to the connection quality at the receiver side. By using the interference cancellation techniques that are energy consuming, and the assumption of sparse TDD cells this problem is solved by LTE-A specs. But this assumption would disappear soon with the increasing implementation of LTE-A in commercial systems and the non-reciprocity will become a serious problem [24].

The consideration of multimedia bidirectional applications and the use of dynamic UL-DL ratio induce more interference in the system because of TDD unsynchronization, and adds another component to the non-reciprocity in the UL-DL channel. Notice that the amount of received interference depends on the selected users in adjacent cells, so that the selection mechanism would need to make an exhaustive search over all possible combinations eNB-user and over all the cells; which is very complex and would need of additional signalling over the system that is not supported by the LTE-A specs.

Therefore, a modified OS selection mechanism is needed for the unsynchronized TDD scenarios [25], that will consider the channel characteristic from the serving eNB to the users in its coverage $\left|h_{s,m}\right|^2$ without the consideration of interference. Obviously, a better scheduler would consider the interference during the unsynchronized region/s, but as we just commented that needs for large signalling. Our objective is to compensate for this situation through a smart energy allocation scheme that we propose in next section.

III. Communication Regions in Unsynchronized TDD

Now that the selection mechanism is presented, we consider the TDD system in a dense urban area, so that there is overlap among several cells, and as they run the TDD system with variable α value for each one, then interference is generated among them. We will characterize the interference patterns and we devise several communication regions that we will tackle separately to show the interference patterns in each one. We identify $M+1$ operating regions that we will denote as R_1 for the DL when the M eNBs are transmitting and the M selected users are receiving their signal, R_2 for the UL when the M selected users transmit to the eNBs; and $M-1$ regions denoted as $R_3, ..., R_{M+1}$ due to the unsynchronization where eNBs and the selected users for the other cells transmit at the same time. Figure (1) shows an example of this environment when $M = 3$ eNBs are considered, where we will tackle its regions now in detail.

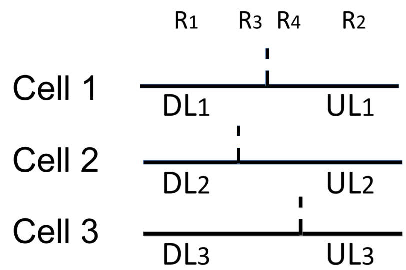

Fig. 1. *The TDD unsynchronized scenario.*

A. DL region in R_1

A unit-power symbols x is transmitted from each eNB with a power value (P_{B1}, P_{B2} and P_{B3} for the first, second and third eNB, respectively). These values should be optimized to ensure the required QoS at the selected user by each eNB, as will be shown in next section. The first eNB within region R_1 transmits its uncorrelated DL symbol $x_{s1,1}$ to its selected user $s1$, making the received signal $y_{s1,1}$ to state as

$$y_{s1,1}{=}h_{s1,1}\, x_{s1,1} \sqrt{P_{B1}} + h_{s1,2}\, x_{s2,2} \sqrt{P_{B2}} +$$

$$+h_{s1,3}\, x_{s3,3} \sqrt{P_{B3}} + z_{s1} \quad (1)$$

where $x_{s2,2}$ and $x_{s3,3}$ are the transmitted signals from the second and third eNBs, respectively to their selected users. z_{s1} is the additive i.i.d. complex Gaussian noise component characterized by zero mean and a variance $E\{|z_n|^2\} = \sigma^2$.

Therefore, the SNIR at the $s1$ selected user in DL ($\text{SNIR}_{s1,R1}$) is obtained as

$$\text{SNIR}_{s1,R1} = \frac{P_{B1}\left|h_{s1,1}\right|^2}{\sigma^2 + P_{B2}\left|h_{s1,2}\right|^2 + P_{B3}\left|h_{s1,3}\right|^2} \quad (2)$$

while for the second eNB, its selected user $s2$ will have

$$\text{SNIR}_{s2,R1} = \frac{P_{B2}\left|h_{s2,2}\right|^2}{\sigma^2 + P_{B1}\left|h_{s2,1}\right|^2 + P_{B3}\left|h_{s2,3}\right|^2} \quad (3)$$

and similarly for the third eNB, its selected user $s3$ gets

$$\text{SNIR}_{s3,R1} = \frac{P_{B3}\left|h_{s3,3}\right|^2}{\sigma^2 + P_{B1}\left|h_{s3,1}\right|^2 + P_{B2}\left|h_{s3,2}\right|^2} \quad (4)$$

B. UL region in R_2

In this region the selected users transmit with a power of P_{s1}, P_{s2} and P_{s3} respectively, while their corresponding eNBs receive their signals in the allocated time for UL. These power values will be optimized as well to ensure the required QoS is satisfied at the eNBs. Remind that in TDD systems reciprocity applies so that the same channel is faced in UL and DL, but with different interference so that different SNIR values are obtained. At the first eNB, its resultant SNIR from its selected user $s1$ ($\text{SNIR}_{s1,R2}$) is formulated as

$$\text{SNIR}_{s1,R2} = \frac{P_{s1}\left|h_{s1,1}\right|^2}{\sigma^2 + P_{s2}\left|h_{s2,1}\right|^2 + P_{s3}\left|h_{s3,1}\right|^2} \quad (5)$$

and the second eNB obtains an SNIR from the signal of its selected user $s2$ as

$$\text{SNIR}_{s2,R2} = \frac{P_{s2}\left|h_{s2,2}\right|^2}{\sigma^2 + P_{s1}\left|h_{s1,2}\right|^2 + P_{s3}\left|h_{s3,2}\right|^2} \quad (6)$$

and similarly for the third eNB, its $s3$ selected user transmitted signal makes the received SNIR value to stand as

$$\text{SNIR}_{s3,R2} = \frac{P_{s3}\left|h_{s3,3}\right|^2}{\sigma^2 + P_{s1}\left|h_{s1,3}\right|^2 + P_{s2}\left|h_{s2,3}\right|^2} \quad (7)$$

C. Unsynchronized region in R_3

The main challenge for the dynamic ratio α implementation in TDD is shown in this region as adjacent cells may have different UL-DL ratio values, as illustrated in figure (1). Within this region, the first and third eNBs are transmitting (in DL) and meanwhile the second eNB is in UL so that its selected user transmits to its eNB, generating cross interference to the other selected users and handicaps the satisfaction of their QoS demands, while the second eNB is also suffering to achieve its QoS requirement. Notice that the second eNB is now receiving interference from the other eNBs transmission (whom are still in DL mode), and the UEs $s1$ and $s3$ are interfered by the signal transmitted from $s2$ that can be close-by. Assuming that the i^{th} and j^{th} selected users have a direct channel between them characterized by h_{s_i,s_j}, and similarly the p^{th} and q^{th} eNB present a direct channel between them as h_{B_p,B_q}; all of them defined by i.i.d. complex Gaussian entries $\sim \mathcal{CN}(0,1)$ but with different distances, and consequently path loss values are different to the channels in previous regions R_1 and R_2.

The first selected user $s1$ is still in DL mode, so that its received SNIR is obtained as

$$\text{SNIR}_{s1,R3} = \frac{P_{B1}\left|h_{s1,1}\right|^2}{\sigma^2 + P_{s2}\left|h_{s1,s2}\right|^2 + P_{B3}\left|h_{s1,3}\right|^2} \quad (8)$$

and the second eNB is in UL so its SNIR value is formulated as

$$\text{SNIR}_{B2,R3} = \frac{P_{s2}\left|h_{s2,2}\right|^2}{\sigma^2 + P_{B1}\left|h_{B1,B2}\right|^2 + P_{B3}\left|h_{B2,B3}\right|^2} \quad (9)$$

while the third selected user is also in DL and its SNIR stands as

$$\text{SNIR}_{s3,R3} = \frac{P_{B3}\left|h_{s3,3}\right|^2}{\sigma^2 + P_{B1}\left|h_{s3,1}\right|^2 + P_{s2}\left|h_{s2,s3}\right|^2} \quad (10)$$

D. Unsynchronized region in R_4

The analysis in this region is very similar to $R3$, and can be extended to any number M of cells as the same pattern will follow, and later when put in a closed form expression, it will be clear that increasing the number of unsynchronized regions would only increase the number of constraints, but has no impact on the capability to formulate the problem nor its convexity.

Looking to figure (1) we notice that both selected users $s1$ and $s2$ are transmitting while the third eNB is still in the DL mode, so the cross interference in this scenario would generate the following SNIR value at the first eNB

$$\text{SNIR}_{B1,R4} = \frac{P_{s1}\left|h_{s1,1}\right|^2}{\sigma^2 + P_{s2}\left|h_{s2,1}\right|^2 + P_{B3}\left|h_{B1,B3}\right|^2} \quad (11)$$

and similarly at the second eNB from the signal sent by its selected user, its obtained SNIR states as

$$\text{SNIR}_{B2,R4} = \frac{P_{s2}\left|h_{s2,2}\right|^2}{\sigma^2 + P_{s1}\left|h_{s1,2}\right|^2 + P_{B3}\left|h_{B2,B3}\right|^2} \quad (12)$$

and finally for the selected user $s3$ still receiving information from its serving eNB with an SNIR value as

$$\text{SNIR}_{s3,R4} = \frac{P_{B3}\left|h_{s3,3}\right|^2}{\sigma^2 + P_{s1}\left|h_{s1,s3}\right|^2 + P_{s2}\left|h_{s2,s3}\right|^2} \quad (13)$$

The objective of this paper within this scenario is to find an optimum energy allocation policy over the values of P_{s1}, P_{s2}, P_{s3}, P_{B1}, P_{B2} and P_{B3} that guarantees the satisfaction for a set of predefined QoS metrics at the receiver sides. The upgrade to any number of overlapping cells is straightforward as more unsynchronized regions will happen and with the formulation of their SNIR values as shown above, they will be all included in the optimization problem in next section.

IV. Energy Allocation Mechanism

In order to enhance the system capabilities, we proposed to use a dynamic UL-DL ratio policy that is variable upon the scenario and applications requirements performance, but such improvement is faced with the problem of TDD unsynchronization among adjacent cells, with the consequent generated interference in the scenario and decreased performance. To keep the benefits of the dynamic ratio, we should find a solution to the generated interference in a way that is low complexity, back-compatible with the LTE-A standard, energy efficient and that can guarantee the QoS satisfaction for multimedia applications. A optimal energy allocation mechanism over all transmitting entities in the network (eNBs and UEs) is required to mitigate the interference and to achieve the QoS demands, and over all the operating regions previously presented. Obviously, such mechanism has to follow a coordinated approach among all involved entities, so that we can categorize it as a Coordinated Multipoint (CoMP) transmission technique [24]. Bear in mind that energy is a crucial resource for wireless systems, because of its effect on cell planning, intercell interference and battery lifetime at UEs.

Different metrics for QoS has been presented in literature for multimedia communication, where the most important ones are the minimum guaranteed data rate and maximum guaranteed error rate that outstand over the others. They are widely used in commercial standards like LTE-A [19] as both are related to the minimum guaranteed SNIR value, which is suitable from the point of view of multimedia applications, as the optimization can be carried out directly on the minimum SNIR value in both the UL and DL. We formulated the optimization problem and obtained the optimal energy allocation in a closed form expression. For easiness to the reader, we present the results for the $M = 3$ cells case, but as already pointed out in the previous section, the extension to any number M is straightforward. Putting the allocation strategy in a mathematically setup, our objective is to minimize the amount of allocated energy subject to a set of QoS requirements as

$$\begin{aligned}
&\min\ E_t\\
&s.t.\ \mathrm{SNIR}_{s1,R1} \geq \xi_d; \quad \mathrm{SNIR}_{s2,R1} \geq \xi_d; \quad \mathrm{SNIR}_{s3,R1} \geq \xi_d\\
&s.t.\ \mathrm{SNIR}_{s1,R2} \geq \xi_u; \quad \mathrm{SNIR}_{s2,R2} \geq \xi_u; \quad \mathrm{SNIR}_{s3,R2} \geq \xi_u\\
&s.t.\ \mathrm{SNIR}_{s1,R3} \geq \xi_d; \quad \mathrm{SNIR}_{B2,R3} \geq \xi_u; \quad \mathrm{SNIR}_{s3,R3} \geq \xi_d\\
&s.t.\ \mathrm{SNIR}_{B1,R4} \geq \xi_u; \quad \mathrm{SNIR}_{B2,R4} \geq \xi_u; \quad \mathrm{SNIR}_{s3,R4} \geq \xi_d
\end{aligned} \tag{14}$$

where ξ_u and ξ_d are the minimum QoS demands for UL and DL, respectively.

QoS satisfaction is related to minimum predefined multimedia demands and the capability of the system to exactly meet them [26]. Any awarded value below the demand will drastically drive the customer unsatisfaction, but any performance higher that requested value will have a marginal enhance of the customer gratification. Thus in order to achieve the highest efficiency of the system resources, an optimization of the allocated energy E_t should be carried out to exactly meet the minimum QoS demands for multimedia applications. From the optimization theory [27], this minimum energy is obtained when the restrictions are met at the exact equality.

Back to our system, as we consider 3 eNBs and 3 UEs in our setup, then the total consumed energy is denoted as

$$\begin{aligned}
E_t = \alpha_1 T_s P_{B1} + (1-\alpha_1) T_s P_{s1} + \alpha_2 T_s P_{B2} + (1-\alpha_2) T_s P_{s2} +\\
+ \alpha_3 T_s P_{B3} + (1-\alpha_3) T_s P_{s3} = \mathbf{r}^T \mathbf{e}
\end{aligned} \tag{15}$$

where α_1, α_2 and α_3 are the UL-DL ratio for the first, second and third eNB, respectively. The energy needed by each transmitter in the system is represented by a loading vector ($\mathbf{e}$) that formulates as

$$\mathbf{e} = T_s \left[P_{B1}, P_{s1}, P_{B2}, P_{s2}, P_{B3}, P_{s3}\right]^T, \tag{16}$$

while the UL-DL ratios are represented by the vector $\mathbf{r}$ as

$$\mathbf{r} = [\alpha_1, (1-\alpha_1), \alpha_2, (1-\alpha_2), \alpha_3, (1-\alpha_3)]^T, \tag{17}$$

Thus, the optimization problem in Eqn. (14) restates as

$$\begin{aligned}
&\min_{\mathbf{e}} \mathbf{r}^T \mathbf{e}\\
&\mathbf{e}(1)\left|h_{s1,1}\right|^2 - \xi_d\left[\sigma^2 + \mathbf{e}(3)\left|h_{s1,2}\right|^2 + \mathbf{e}(5)\left|h_{s1,3}\right|^2\right] \geq 0\\
&\mathbf{e}(3)\left|h_{s2,2}\right|^2 - \xi_d\left[\sigma^2 + \mathbf{e}(1)\left|h_{s2,1}\right|^2 + \mathbf{e}(5)\left|h_{s2,3}\right|^2\right] \geq 0\\
&\mathbf{e}(5)\left|h_{s3,3}\right|^2 - \xi_d\left[\sigma^2 + \mathbf{e}(1)\left|h_{s3,1}\right|^2 + \mathbf{e}(3)\left|h_{s3,2}\right|^2\right] \geq 0\\
&\mathbf{e}(2)\left|h_{s1,1}\right|^2 - \xi_u\left[\sigma^2 + \mathbf{e}(4)\left|h_{s2,1}\right|^2 + \mathbf{e}(6)\left|h_{s3,1}\right|^2\right] \geq 0\\
&\mathbf{e}(4)\left|h_{s2,2}\right|^2 - \xi_u\left[\sigma^2 + \mathbf{e}(2)\left|h_{s1,2}\right|^2 + \mathbf{e}(6)\left|h_{s3,2}\right|^2\right] \geq 0\\
&\mathbf{e}(6)\left|h_{s3,3}\right|^2 - \xi_u\left[\sigma^2 + \mathbf{e}(2)\left|h_{s1,3}\right|^2 + \mathbf{e}(4)\left|h_{s2,3}\right|^2\right] \geq 0\\
&\mathbf{e}(1)\left|h_{s1,1}\right|^2 - \xi_d\left[\sigma^2 + \mathbf{e}(4)\left|h_{s1,s2}\right|^2 + \mathbf{e}(5)\left|h_{s1,3}\right|^2\right] \geq 0\\
&\mathbf{e}(4)\left|h_{s2,2}\right|^2 - \xi_u\left[\sigma^2 + \mathbf{e}(1)\left|h_{B1,B2}\right|^2 + \mathbf{e}(5)\left|h_{B2,B3}\right|^2\right] \geq 0\\
&\mathbf{e}(5)\left|h_{s3,3}\right|^2 - \xi_d\left[\sigma^2 + \mathbf{e}(1)\left|h_{s3,1}\right|^2 + \mathbf{e}(4)\left|h_{s2,s3}\right|^2\right] \geq 0\\
&\mathbf{e}(2)\left|h_{s1,1}\right|^2 - \xi_u\left[\sigma^2 + \mathbf{e}(4)\left|h_{s2,1}\right|^2 + \mathbf{e}(5)\left|h_{B1,B3}\right|^2\right] \geq 0\\
&\mathbf{e}(4)\left|h_{s2,2}\right|^2 - \xi_u\left[\sigma^2 + \mathbf{e}(2)\left|h_{s1,2}\right|^2 + \mathbf{e}(5)\left|h_{B2,B3}\right|^2\right] \geq 0\\
&\mathbf{e}(5)\left|h_{s3,3}\right|^2 - \xi_d\left[\sigma^2 + \mathbf{e}(2)\left|h_{s1,s3}\right|^2 + \mathbf{e}(4)\left|h_{s2,s3}\right|^2\right] \geq 0
\end{aligned} \tag{18}$$

that even it shows a lot of restrictions to be satisfied, but it is formulated as a linear optimization problem. We can carry out the optimization through computer based tools as SeDuMi and Fmincon, but we also obtain it in a mathematical closed form expression as we accomplish the optimization at the optimum point ($\mathbf{e}^*$), where the inequalities become equalities [27]:

$$\mathbf{e}^* = \mathbf{K}^{-1}\mathbf{n}, \qquad E_t(\mathbf{e}^*) = \mathbf{r}^T\mathbf{e}^* = \mathbf{r}^T\mathbf{K}^{-1}\mathbf{n}, \tag{19}$$

where $\mathbf{n} \in \mathcal{R}^{M(M+1)\times 1}$ is defined as

$$\mathbf{n} = \sigma^2\left[\xi_d, \xi_d, \xi_d, \xi_u, \xi_u, \xi_u, \xi_d, \xi_u, \xi_d, \xi_u, \xi_u, \xi_d\right]^T \tag{20}$$

and $\mathbf{K} \in \mathcal{R}^{M(M+1)\times 2M}$ is given in Eqn.(21) at the beginning of next page.

The formulated mathematical solution not only avoids the long computer simulations, but it also enables to test the problem feasibility, as not all customer requirements can be satisfied (due to channel conditions, application requirements and/or interference). The unfeasibility of the demand is indicated through a negative value of its corresponding entry in $\mathbf{e}$. The solution is by changing the scenario setup, the UL-DL ratios or the users requirements to be changed. Notice that the increase in the number of cells M would induce more equations, a larger $\mathbf{K}$, $\mathbf{r}$ and $\mathbf{n}$ dimensions, but the problem will keep being a linear optimization problem with the same solution as in Eqn.(19).

V. Computer Simulations

Our proposed energy optimization strategy is tackled by computer simulations within the TDD UL-DL environment where the adjacent cells are unsynchronized. The objective is to show the role of the different variables that affect the system behaviour, as well as to show its benefits when compared to benchmark techniques. To test our algorithm, we use Monte Carlo simulations over 1000 different scenarios, each one of them following the system model presented in section II. An LTE-A system is considered and its parameters are tackled, so that in a $1ms$ TTI length, we can transmit 7 symbols.

$M = 3$ cells are considered with a full bandwidth reuse. 10 single-antenna users are available in each cell and they are serviced by a single-antenna eNB that applies the modified opportunistic scheduling mechanism. Without loss of generality, the same multimedia demands for UL and DL are considered, i.e. $\xi_u = \xi_d$. For the mathematical calculations, we follow Eqn.(19) to obtain the amount of allocated energy to each selected user and to each eNB. The cells are circular but affected by path loss and channel fluctuations presented in section II. The eNBs are 5 Kms away from each other, noise variance is $\sigma^2 = 1$, and its operating frequency is 1 GHz. The values of $\alpha_1 = 0.5$ and $\alpha_2 = 0.4$ are tackled on the basis of the applications' requirements, scenario characteristics, traffic demands and/or operator policy. Therefore, an unsynchronized TDD system is obtained among its operating cells.

To illustrate the system behaviour, the probability of QoS satisfaction is presented for a variable users' requirement. To understand the proposed scheme performance, we compare it to a blind system to unsynchronization that assumes the same ratio UL-DL over all its cells (i.e., same α). Also we show results from the traditional systems where all entities transmit with their maximum allowed energy. Figure (2) plots the percentage of users that get satisfied with the provided service, as their QoS demands are met whatever is their application request. Clearly from the figure, our proposed allocation strategy presents better performance than the other 2 schemes, as for all the users' demands, it delivers higher QoS satisfaction. Our algorithm to find the optimal amount of energy to each entity in the system includes a minimum SNIR for both the UL and DL, so a minimum SNIR value is always guaranteed, that can be seen as a QoS indicator in the system. This is actually a very realistic aspect of QoS, as operators would like to ensure the exact SNIR value the customer paid for (e.g., 2Mbps for 19 euros/month), so the SNIR value is linked to a certain Mbps value along the LTE-A standard mapping tables rate-SNIR [23] or through the theoretical Shannon rule. It is observed that a larger number of users drives down the QoS probabilities and for all schemes, to the extent that they can make the energy allocation techniques to be unfeasible.

We should compare the behaviour of our proposal to others in literature, but unfortunately, there are no other algorithms in literature to tackle this issue. This is why we compare it to the cases of fixed α value and/or the fixed energy protocol.

Another advantage of our scheme is the energy optimization and how it will achieve the same QoS satisfaction, but with a lower amount of consumed energy when compared to other strategies. Figure (3) plots our proposal together with the benchmark technique of full energy transmission, as a comparison to the unaware TDD unsynchronization scheme is not fair; and for variable QoS requirements. The figure shows the amount of energy consumption and how our proposal provides lower consumption and for all QoS demands values, while we fix the QoS performance for both techniques.

VI. Conclusions

This paper illustrated the suitability of our proposed technique when the TDD cells UL-DL ratio is variable and adapts to the multimedia applications requirements and scenario characteristics, through a dynamic α value that generates interference among the cells as they are unsynchronized, and how our proposal mitigates the generated interference. We formulated the energy allocation as an optimization problem and we solved it mathematically to obtain the optimum energy allocation to guarantee the minimum energy consumption, while Quality of Service (QoS) demands are satisfied at all communication entities (UEs and eNBs).

The optimization of the α values are out of the paper scope and left as a future work. The consideration of handover

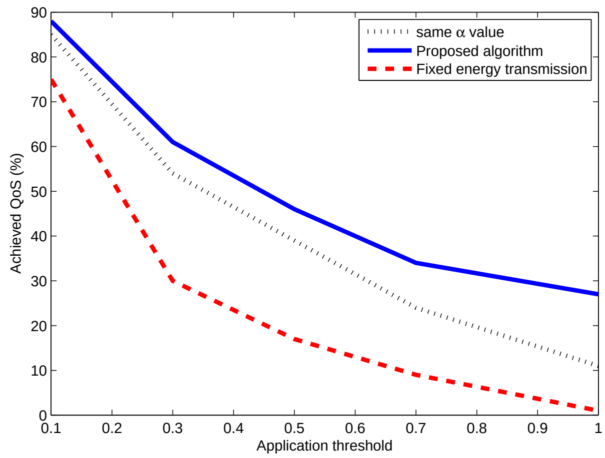

Fig. 2. *The obtained QoS satisfaction and for a variable application requirement.*

$$
\mathbf{K}=\begin{bmatrix}
|h_{s1,1}|^2 & 0 & -\xi_d|h_{s1,2}|^2 & 0 & -\xi_d|h_{s1,3}|^2 & 0\\
-\xi_d|h_{s2,1}|^2 & 0 & |h_{s2,2}|^2 & 0 & -\xi_d|h_{s2,3}|^2 & 0\\
-\xi_d|h_{s3,1}|^2 & 0 & -\xi_d|h_{s3,2}|^2 & 0 & |h_{s3,3}|^2 & 0\\
0 & |h_{s1,1}|^2 & 0 & -\xi_u|h_{s2,1}|^2 & 0 & -\xi_u|h_{s3,1}|^2\\
0 & -\xi_u|h_{s1,2}|^2 & 0 & |h_{s2,2}|^2 & 0 & -\xi_u|h_{s3,2}|^2\\
0 & -\xi_u|h_{s1,3}|^2 & 0 & -\xi_u|h_{s2,3}|^2 & 0 & |h_{s3,3}|^2\\
|h_{s1,1}|^2 & 0 & 0 & -\xi_d|h_{s1,s2}|^2 & -\xi_d|h_{s1,3}|^2 & 0\\
-\xi_u|h_{B1,B2}|^2 & 0 & 0 & |h_{s2,2}|^2 & -\xi_u|h_{B2,B3}|^2 & 0\\
-\xi_d|h_{s3,1}|^2 & 0 & 0 & -\xi_d|h_{s2,s3}|^2 & |h_{s3,3}|^2 & 0\\
0 & |h_{s1,1}|^2 & 0 & -\xi_u|h_{s2,1}|^2 & -\xi_u|h_{B1,B3}|^2 & 0\\
0 & -\xi_u|h_{s1,2}|^2 & 0 & |h_{s2,2}|^2 & -\xi_u|h_{B2,B3}|^2 & 0\\
0 & -\xi_d|h_{s1,s3}|^2 & 0 & -\xi_d|h_{s2,s3}|^2 & |h_{s3,3}|^2 & 0
\end{bmatrix} \tag{21}
$$

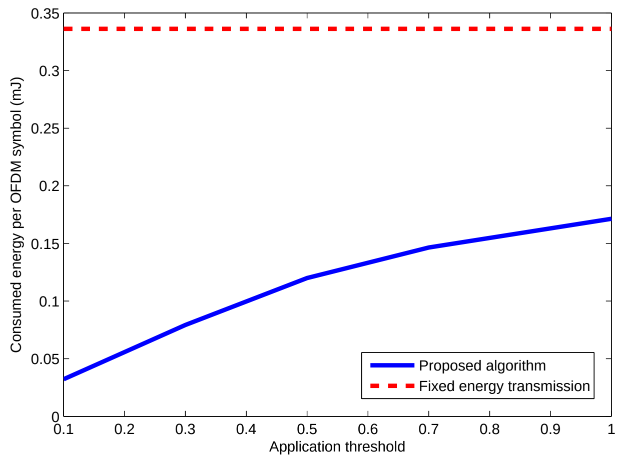

Fig. 3. *The amount of energy consumption for a variable application requirement.*

among the cells will definitely impact the system performance and it is also left as a future work.

References

[1] P. Bhat *et al.*, "LTE-advanced: An Operator Perspective," *IEEE Communications Magazine*, vol. 50, no. 2, February 2012.

[2] P. Solis and J. Saunders, "TDD LTE Making the most of 4G," *ABI Research*, September 2012.

[3] D. Schoolar, 'LTE TDD goes mainstream - Huawei Study," *Ovum Research*, November 2012.

[4] W. Vereecken *et al.*, "Power consumption in telecommunication networks: overview and reduction strategies," *IEEE Communications Magazine*, vol. 49, no.6, pp. 62-69, June 2011.

[5] A. Puggelli *et al.*, "Routing-Aware Design of Indoor Wireless Sensor Networks Using an Interactive Tool," *IEEE Systems Journal*, no.99, pp.1-14, October 2013.

[6] Y. Lan and A. Harada, "Power Allocation-Based Adjacent Channel Interference Reduction for Coexisting TD-LTE and LTE-FDD Networks", *IEEE VTC*, Dresden, Germany, June 2013.

[7] Y. Zhao, X. Fang, R. Huang, and Y. Fang, "Joint Interference Coordination and Load Balancing for OFDMA Multihop Cellular Networks", *IEEE Transactions on Mobile Computing*, vol.13, no.1, pp:13-21, January 2014.

[8] L. Zhang, X. Ji, M. Peng, "A rank adaptive beamforming scheme for TDD LTE system with imperfect CSI", *IEEE WCSP*, Huangshan, China, October 2012.

[9] P. Tarasak, K. Adachi and S. Sun, "Cell Selection for TDD Two-Tier Cellular Networks based on Uplink-Downlink Capacity", *IEEE WCNC*, Shanghai, China, April 2013.

[10] M. Peng *et al.*, "Performance of Dual-Polarized MIMO for TD-HSPA Evolution Systems," *IEEE Systems Journal*, vol.5, no.3, pp. 406-416, March 2011.

[11] Y. Kim, G. Miao, and T. Hwang, "Energy Efficient Pilot and Link Adaptation for Mobile Users in TDD Multi-User MIMO Systems", *IEEE Transactions on Wireless Communications*, March 2014.

[12] K. Samdanis, R. Shrivastava, A. Prasad, P. Rost, and D. Grace, "Virtual Cells: Enhancing the Resource Allocation Efficiency for TD-LTE", *IEEE VTC Fall*, Vancouver, Canada, September 2014.

[13] X. Liu, L. Wang, D. Liu, W. Guo, and Q. Quan, "Energy-efficient algorithm for carrier aggregation and cognitive radio based TD-LTE system", *Information and Communications Technologies (ICT 2014)*, Nanjing, China, May 2014.

[14] A. Kini, M. Hosseinian, P. Sadeghi, and J. Stern-Berkowitz, "A dynamic subframe set power control scheme for interference mitigation in reconfigurable TD-LTE systems", *Wireless and Optical Communication Conference (WOCC)*, Newark, USA, May 2014.

[15] A. Bourdena *et al.*, "An Energy-Aware Scheme for Efficient Spectrum Utilization in a 5G Mobile Cognitive Radio Network Architecture", *Special Issue on Energy Efficient 5G Wireless Technologies, Springer Telecommunication Systems Journal*, January 2015.

[16] A. Bourdena *et al.*, "A Resource Intensive Traffic-Aware Scheme using Energy-efficient Routing in Cognitive Radio Networks, *Elsevier Future Generation Computer Systems Journal*, vol.39, pp. 16-28, October 2014.

[17] Y. Kryftis *et al.*, "Resource Usage Prediction for Optimal and Balanced Provision of Multimedia Services, *IEEE CAMAD*, Athens, Greece, December, 2014.

[18] H. Abou-Zeid, N. Zorba and H. Hassanein, "Enhancing Mobile Video Streaming by Lookahead Rate Allocation in Wireless Networks", *IEEE CCNC*, Las Vegas, USA, January 2014.

[19] R. Kwan and C. Leung, "A survey of scheduling and interference mitigation in LTE," *Journal of Electrical and Computer Engineering*, vol. 2010, no.1, January 2010.

[20] A.M. El-Hajj and Z. Dawy, "Dynamic Joint Switching Point Configuration and Resource Allocation in TDD-OFDMA Wireless Networks", *IEEE GLOBECOM*, Houston, USA, December 2011.

[21] P. Viswanath, D. Tse and R. Laroia, "Opportunistic Beamforming using Dumb Antennas", *IEEE Transactions on Information Theory*, vol. 48, June 2002.

[22] Y. Wu *et al.*, "Optimal Beaconing Control in Delay-Tolerant Networks With Multiple Destinations," *IEEE Systems Journal*, no.99, pp. 1-10, October 2014.

[23] 3GPP TR36.828, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further enhancements to LTE Time Division Duplex (TDD) for Downlink-Uplink (DL-UL) interference management and traffic adaptation", July 2014.

[24] X. Ping, L.C. Hung and J.G. Andrews, "Downlink Coordinated Multi-Point with Overhead Modeling in Heterogeneous Cellular Networks", *IEEE Transactions on Wireless Communications*, vol.12, no.8, August 2014.

[25] N. Zorba, E. Yaacoub and C. Verikoukis, "Energy Optimization in Unsynchronized TDD Systems for Joint Uplink Downlink Scheduling", *IEEE-Globecom*, Atlanta, USA, December 2013.

[26] N. Zorba, A.I. Perez-Neira, A. Foglar and C. Verikoukis, "Cross Layer QoS Guarantees in Multiuser WLAN Systems", Springer Wireless Personal Communications, volume 51, November 2009.

[27] M. Biguesh, S. Shahbazpanahi and A.B. Gershman, "Robust Downlink Power Control in Wireless Cellular Systems", *EURASIP-JWCN*, vol. 2004, no.2, December 2004.